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Innovative Design of a Continuous Ultrasound Bath for Effective Lignocellulosic Biomass Pretreatment Based on a Theorical Method

Paula Andrea Ramirez Cabrera, Alejandra Sophia Lozano Pérez * and Carlos Alberto Guerrero Fajardo

Departamento de Química-Facultad de Ciencias, Universidad Nacional de Colombia, Sede Bogotá 111321, Colombia
* Correspondence: aslozanop@unal.edu.co

Abstract: Ultrasonic pretreatment is a crucial step in the bioconversion of lignocellulosic biomass, such as peapods, into valuable products. Ultrasonic pretreatment is a highly effective physical method that utilizes ultrasonic waves to enhance various processes. Biomass pretreatment is achieved through physical effects such as acoustic cavitation, which disrupts the biomass structure, and chemical effects like radical formation, which breaks down complex molecules. This article focuses on the characteristics, types, and applications of ultrasonic pretreatment in peapods, with a particular emphasis on its role in lignin removal and ultrasound design. An innovative mechanical design in a CAD application of a continuous ultrasound treatment with a capacity of 5 L and an FEA analysis of the equipment are presented as results, providing insights for the design and optimization of ultrasonic pretreatment processes.

Keywords: ultrasonic pretreatment; continuous ultrasound design; biomass; ultrasonic bath; hydrolysis; sustainable energy

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1. Introduction

The increase in pollution from the different conventional energy sources and the quantities of waste produced under biological processes have led to the development of renewable energy sources and the use of organic matter, known as biomass. Lignocellulose biomass is the most abundant resource produced in the agri-food industry from food and plants. This biomass is eliminated by burning or degradation, and these are processes that generate pollution. However, research has shown that it can be valorized through transformation processes, such as chemical, physical, and biological processes [1]. Lignocellulose biomass is a low-cost, carbon-neutral, heterogeneous organic polymer [2]. It is composed of 40–60%wt cellulose, 25–35%wt hemicellulose, 15–40%wt lignin, and other compounds like protein, pectin, ash, and extractives. Thanks to these components, it is possible to obtain usable products for biofuels and sugars, among others [1]. The composition varies with the type of biomass, soil, climate, fertilizers, growing conditions, and harvesting technique, among others [2].

Valorization processes have been developed with technologies such as the well-known biorefineries, in which several processes can be integrated to improve the efficiency and use of lignocellulose biomass; moreover, this contributes to the development of a circular bioeconomy. However, it requires a large amount of energy consumption when lignocellulose biomass is used in the process. Pretreatments are important because they change the crystalline structure of the biomass, breaking the bonds between cellulose, hemicellulose, and lignin. This makes subsequent processes more effective because it improves the access to cellulose, which is a compound of interest for the processes of utilization in obtaining products and also decreases the degree of polymerization. The pretreatment conditions vary according to the type of biomass, structural properties, composition, and degree of polymerization [2].

The chemical pretreatment of biomass involves the use of organic or inorganic compounds to disrupt the biomass structure, making it more accessible for enzymatic hydrolysis [3]. This also makes it easier to convert biomass into useful products. Chemical pretreatment can be achieved through various methods, including acid, alkali, and organic solvent pretreatments. Acid pretreatment involves the use of dilute or concentrated acids to hydrolyze hemicellulose and lignin [3]. Alkali pretreatment, on the other hand, employs alkali to degrade lignin. Organic solvent pretreatment involves the use of organic solvents to extract lignin and hemicellulose. All of these make the cellulose more accessible for enzymatic hydrolysis [4]. Advanced, greener chemical pretreatments of biomass have been developed, utilizing sources of renewable energy such as solar, wind, and biomass [5]. These methods suitably combine physical, greener, and enzymatic methods to achieve the desired outcomes. The chemical pretreatment of lignocellulosic biomass with acids, alkalis, and organic solvents is considered one of the most promising methods, as it can increase the efficiency of enzymatic hydrolysis and the subsequent conversion of the biomass into useful products [6].

Biological pretreatments of biomass involve the use of microorganisms, such as fungi and bacteria, to degrade lignin and hemicellulose, making the cellulose more accessible for enzymatic hydrolysis [7]. This type of method has the advantage of being highly cost-effective and can be divided into fungi, bacteria, microbial consortium, and enzyme treatments [8]. Fungi, such as white rot fungi and brown rot fungi, are widely used in the microbial treatment of lignocellulose, with white rot fungi being preferred due to their high selectivity in lignin degradation. Bacteria, which are mostly isolated from the environment, have strong viability but limited degradation abilities, while microbial consortia combining multiple strains are applied for high-efficiency production. The direct application of enzymes is another treatment method, with the corresponding enzymes selected based on the substrate structure for targeted treatment [8].

Physical pretreatments of biomass involve various methods aimed at altering the structure of the lignocellulosic biomass to enhance its accessibility for further processing. These methods include milling, extrusion, ultrasound, and microwave radiation, which utilize mechanical or wave energy to modify the biomass structure, affecting parameters like the pore space, grain size, crystallinity, amorphous cellulose, and surface area [9]. The primary goal of physical pretreatment is to reduce the particle size through mechanical comminution, increasing the surface area and pore size of the biomass, which in turn facilitates enzymatic hydrolysis and subsequent conversion processes [9]. Physical pretreatments play a crucial role in breaking down the complex structure of biomass, making it more amenable to downstream processes for biofuel and biochemical production.

The use of ultrasound for the pretreatment of biomass has been previously explored in the literature. Various studies have investigated the application of high-intensity ultrasonication, which utilizes high-frequency sound waves to induce cavitation and disrupt the lignocellulosic structure of biomass [10,11]. This approach has been shown to enhance the accessibility of cellulose and hemicellulose for enzymatic hydrolysis, leading to improved sugar yields [12]. For example, a previous study demonstrated that the high-intensity ultrasonication of corn stover at 100 W and 20 kHz for 30 min increased the glucose yield by 355% compared to untreated biomass [13].

Alternatively, low-intensity ultrasonication has also been investigated as a pretreatment method. While less disruptive to the biomass structure, low-intensity ultrasound can still enhance the biomass digestibility through mechanisms such as improved mass transfer and an increased surface area [14]. For instance, a study found that subjecting switchgrass to low-intensity ultrasonication at 20 kHz for 72 h increased the sugar yield to 93% during enzymatic hydrolysis [15]. The combination of ultrasonic pretreatment with other methods, such as chemical or thermal pretreatment, has also demonstrated synergistic effects in improving the accessibility and conversion of biomass [16].

Ultrasound is crucial as a physical pretreatment for biomass due to its ability to enhance the breakdown of lignocellulosic materials, improving the efficiency of biomass conversion processes. Unlike chemical pretreatment approaches that often involve harsh conditions and the use of acids or bases, the continuous ultrasound bath utilizes a physical pretreatment mechanism that does not introduce corrosive reagents. By avoiding the generation of inhibitory byproducts like hydroxymethylfurfural (HMF), furfural, and organic acids, which can severely inhibit the activity of cellulolytic enzymes and microorganisms, the continuous ultrasound bath provides a more benign pretreatment process that preserves the integrity of the feedstock for subsequent enzymatic hydrolysis or fermentation steps [17]. This article aims to discuss different types of ultrasound techniques and to elucidate their mechanisms of action, highlighting how they facilitate biomass treatment by leveraging acoustic cavitation and other ultrasound-related effects to enhance biomass' conversion into value-added products. Additionally, the present article aims to present a mathematical model and computer-aided design (CAD) for an ultrasonic system tailored to valorizing biomass, showcasing the integration of advanced technology to optimize the pretreatment process and maximize the production of valuable bio-based products.

The proposed continuous ultrasound bath aims to address a key limitation of conventional ultrasound baths—the problem of solvent saturation over time. In traditional ultrasound baths, the static solvent (e.g., water, organic solvent) becomes increasingly saturated with extractives, reducing the effectiveness of the ultrasonic pretreatment. The continuous ultrasound bath incorporates a flow system that allows for the constant replenishment of the solvent, preventing the drop in extraction and efficiency and increasing the consistency of the ultrasound-based process over a longer period of time. This approach can lead to better results and reduced maintenance requirements compared to conventional ultrasound baths that lack a continuous flow.

2. Ultrasonic Pretreatment

Ultrasonic pretreatment is a highly effective physical method that utilizes ultrasonic waves to enhance various processes, particularly in the treatment of sludge and organic pollutants. This technique involves the application of high-frequency sound waves to a medium, creating cavitation bubbles that implode, generating intense localized heat and pressure [9]. It utilizes ultrasonic waves with frequencies ranging from 18 kHz to 10 MHz. Ultrasonic waves can be divided into high-frequency and low-frequency ultrasound. The frequency of high-frequency ultrasound is over 1 MHz and it is mainly used for non-destructive food testing, quality evaluation, and process control to ensure the quality and safety of food. The frequency of low-frequency ultrasound ranges from 18 to 100 kHz and it is mainly used in food processing, such as extraction, the enzymolysis of proteins, the modification of starch, sterilization, the inactivation of enzymes, washing, and other applications [18].

The cavitation phenomenon induced by ultrasound plays a crucial role in sonochemistry, creating microreactors that accelerate reactions and enable novel processes to occur safely [19]. Ultrasonic pretreatment has been extensively studied and applied in various fields, showcasing its efficiency in enhancing the disintegration of organic pollutants and improving the biodegradability of sludge.

The process of ultrasonic pretreatment involves several key steps, including the compression and rarefaction of the medium; cavitation bubble formation; bubble collapse, generating shock waves; and the creation of microscopic channels in the medium (Figure 1). These steps are essential in breaking down the complex structures of organic pollutants and sludge, making them more amenable to further treatment processes [19]. Ultrasonic pretreatment has been recognized as an emerging and effective mechanical method to enhance the biodegradability of sludge, offering a green technology approach through the principle of cavitation induced by ultrasonic radiation. This technique has shown promising results in enhancing the efficiency of anaerobic digestion processes and improving the overall treatment of various organic materials.

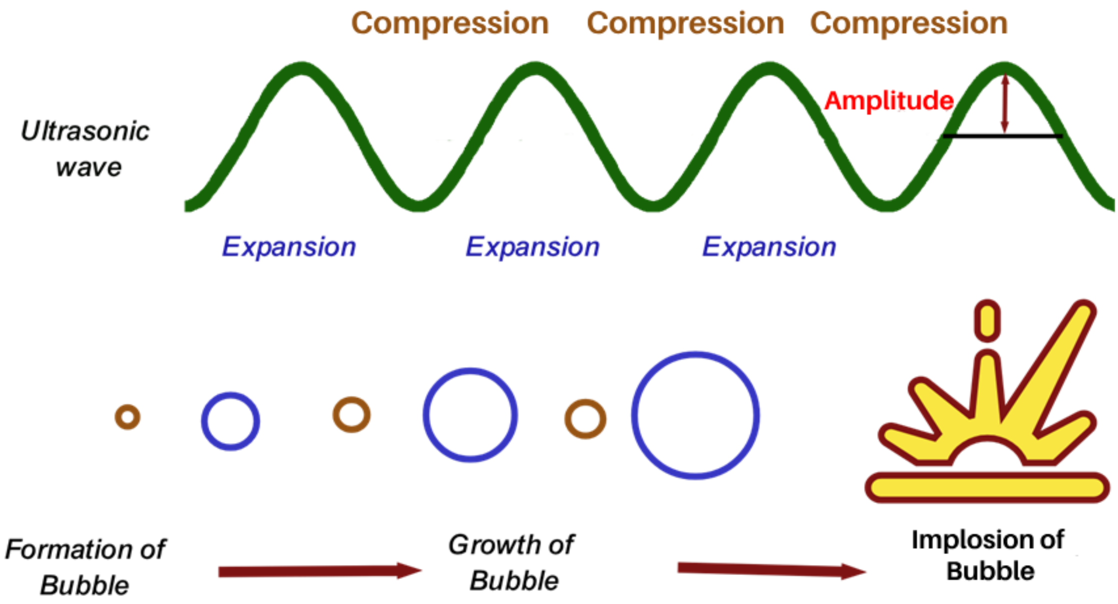


Figure 1. Key steps for the process of ultrasonic pretreatment.

The ultrasonic parameters that greatly affect the cavitation effect mainly include the ultrasonic frequency, intensity, and ultrasonic transducer design. The ultrasonic frequency plays a crucial role in the yield of sonochemical reactions. However, a single-frequency ultrasonic cleaning tank (bath) and ultrasonic cell crusher (probe) are widely used in research work. There are widespread problems such as excessive ultrasonic power and uneven sound field distribution, hindering the use of ultrasound in food processing. These problems seriously restrict the theoretical research, technical development, and industrial application of ultrasonic technology [20].

3. Ultrasonic Set-Ups

3.1. Ultrasonic Bath Configuration

Ultrasonic bath configurations are commonly used setups when conducting sonochemical reactions, particularly in the valorization of biomass. In an ultrasonic bath, a container is filled with a liquid medium, such as water or a solvent, and an ultrasonic transducer is immersed in the liquid [21]. The transducer generates high-frequency sound waves above 20 kHz, which propagate through the liquid, creating cavitation bubbles. These bubbles implode, generating intense localized heat and pressure, which leads to the breakdown of biomass structures and facilitates chemical reactions [22].

To use an ultrasonic bath for biomass valorization, the sample (biomass material) is typically placed in a suitable container or vessel that can be immersed in the liquid inside the ultrasonic bath (Figure 2). The container holding the sample should be positioned in such a way that it is fully submerged in the liquid to ensure the efficient transmission of ultrasonic energy to the biomass material [23]. The ultrasonic bath is then activated, and the high-frequency sound waves induce cavitation in the liquid, enhancing the breakdown of the biomass and promoting chemical reactions for valorization purposes. A transducer in an ultrasonic bath works by converting electrical energy into mechanical energy, which generates ultrasonic waves in the liquid medium. The transducer is typically attached to the bottom or sides of the bath, and it vibrates at a high frequency, causing the liquid to vibrate as well. This vibration creates cavitation bubbles in the liquid, which implode and generate high temperatures and pressure, leading to the breakdown of the biomass and the promotion of chemical reactions for valorization purposes [24].

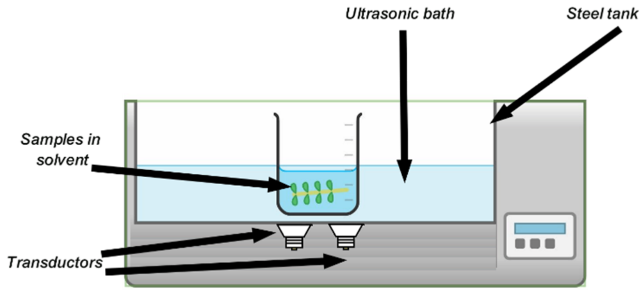


Figure 2. Ultrasonic bath for biomass valorization.

Table 1 presents some previous research on biomass valorization applying an ultrasonic bath set-up.

Table 1. Research on biomass valorization applying an ultrasonic bath set-up.

Feedstock	Microwave Set-Up	Conditions	Desired Product/Process	Source
Sugarcane straw	Ultrasonic bath	25 kHz, 30 min, H2O2 (15% *v*/*v*), 70 °C	Demineralization (66%)	[25]
Nannochloropsis sp.	Ultrasonic bath	Methanol/hexane (20.5 mL/47.5 mL), 34 °C, 60 min	Lipid extraction (8.9%)	[26]
Ocimum basilicum L.	Ultrasonic bath	75% ethanol at 45 °C 20 kHz and 100 W for 15 min	Polyphenols	[27]
Fique fibers, fique tow, fique pulp	Ultrasonic bath	22 kHz, 130 W, 1 h, 40 °C	Lignin removal (79–88%)	[28]
Sunn hemp	Ultrasonic bath	50 Hz, 50 °C, 1 h	Lignin reduction (2%)	[29]
Invasive weeds	Ultrasonic bath	(35 kHz, 35 W and 10% duty cycle) for 12 h	Ethanol increased from 147 g/kg to 220 g/kg	[30]

3.2. Ultrasonic Probe in Bath

An ultrasonic probe configuration for biomass pretreatment involves the use of a high-frequency sound wave generator, known as an ultrasonic probe, to induce cavitation in the liquid medium containing the biomass sample. The probe is typically immersed in the liquid and positioned in close proximity to the biomass sample (Figure 3). The high-frequency sound waves generated by the probe create cavitation bubbles in the liquid, which implode and generate intense localized heat and pressure. This cavitation phenomenon enhances the breakdown of the biomass and promotes chemical reactions for valorization purposes.

In an ultrasonic bath, the ultrasonic waves are generated by an ultrasonic transducer located at the bottom or side of the container. The transducer vibrates at a high frequency, generating ultrasonic waves that propagate through the liquid medium and induce cavitation in the biomass sample. Ultrasonic baths are commonly used for large-scale biomass pretreatment and can handle a large amount of feedstock. However, they typically require mechanical agitation to ensure the efficient transmission of ultrasonic energy to the biomass material [31].

On the other hand, in an ultrasonic probe, also known as an ultrasonic horn or sonotrode, a high-intensity ultrasonic transducer is directly immersed in the biomass sample. Ultrasonic probes are commonly used for small-scale biomass pretreatment and can handle a smaller amount of feedstock compared to ultrasonic baths. However, they offer higher energy efficiency and better control over the ultrasonic treatment parameters.

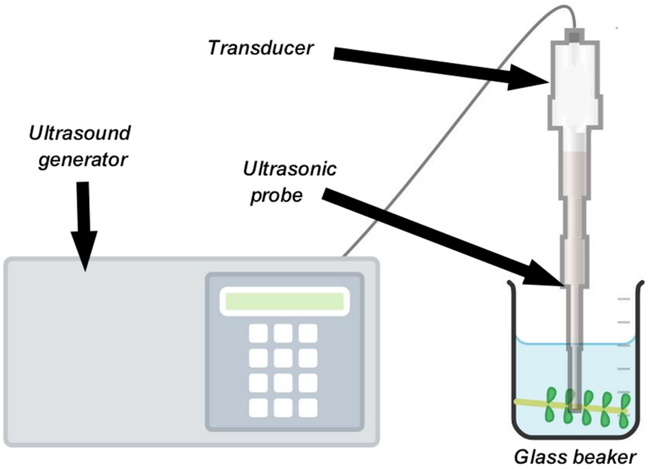


Figure 3. Probe in ultrasonic bath.

In terms of biomass valorization, both ultrasonic bath and ultrasonic probe configurations have been used for the pretreatment of various types of biomass, including agricultural residues, lignocellulosic biomass, and algal biomass. The use of ultrasound probes as a pretreatment technique has shown improvements in by-product production, as presented in Table 2.

Table 2. Research on biomass valorization applying an ultrasonic probe set-up.

Feedstock	Microwave Set-Up	Conditions	Desired Product/Process	Source
Mango peel	Sonotrode	55/45 ethanol/water (*v*/*v*), 18 min, and 65% amplitude	Phenolic compounds (+33%)	[32]
Apple pomace	Sonotrode	6/10 (*w*/*w*) feedstock/water, UP400St ultrasonic processor, 50% ethanol, 23 min, and 65% amplitude	Phenolic compounds	[33]
Orange by-products	Sonotrode	45/55 ethanol/water (*v*/*v*), 35 min, amplitude 90% (110 W), and pulse 100%	Phenolic content	[33]
Cellulose	Sonotrode	1 kW, HTL reactor, 3% KOH	-	[34]
Cinnamomum cassia	Sonotrode	Solid loading 25 g, ultrasound power 600 W, 35 min, solvent quantity 100 mL, yield of 3.17%	Bark oil	[35]
Microalgae	Sonotrode	200 W, 24 kHz, chloroform/methanol/water ratio (2:1:1.8)	Microalgae hydrolysate	[36]

4. Condition Optimization

The parameters for ultrasonic-assisted reactions include the amplitude of the ultrasound, the solvent type, and the reaction time, as well as the frequency and wattage of the ultrasonic system.

The amplitude of the ultrasound refers to the maximum displacement of the ultrasonic transducer from its equilibrium position, which affects the intensity of the ultrasound waves. In the context of ultrasound-mediated radical cascade reactions, the amplitude of the ultrasound was shown to significantly impact the conversion rate of the reaction [37]. For example, using 40% of the amplitude for 30 s led to poor conversion to product 2a, while increasing the amplitude to 60% led to 98% conversion. Similarly, when 60% of the amplitude was applied for 60 s, 98% conversion was achieved. Therefore, the amplitude of the ultrasound is an important parameter to optimize in ultrasonic-assisted reactions.

The solvent type is an important parameter in ultrasonic-assisted reactions because it can significantly affect the efficiency of the extraction process. The solvent can influence the cavitation threshold, the solubility of the reactants, and the mass transfer rate during the reaction. For example, in the synthesis of functionalized indolines, the researchers optimized the solvent type to achieve the high conversion of the reactants [38]. The choice of solvent can affect the solubility and reactivity of the reactants, as well as the stability of the intermediates and products. Therefore, selecting the appropriate solvent is crucial in maximizing the yield and selectivity of the reaction. In ultrasonic-assisted extraction, the solvent type plays an important role in the extraction of essential oils [39]. The solvent's selection is critical in ultrasound-assisted extraction (UAE), mainly due to its effect on mass transfer and cavitation. The solvent's density decreases, resulting in the acceleration of mass transfer and an increase in the number of cavitation bubbles within the fluid. This cushioning effect can eventually cause the ultrasound cavitation effect to be less efficient if the temperature is too high.

The reaction time is a critical parameter in ultrasound-assisted reactions, as it determines the duration of ultrasonic irradiation, which can affect the conversion of reactants. In the ultrasound-assisted synthesis of functionalized indolines, the reaction time was shown to impact the conversion rate of the reaction, with longer sonication times leading to higher conversion rates [40]. Ultrasound-assisted reactions can enhance chemical synthesis through cavitation effects, which produce localized hot spots exceeding 4000 K that can drive homogeneous and heterogeneous reactions. Homogeneous reactions involve single-phase systems and produce radicals from water sonolysis, while heterogeneous reactions involve multi-phase systems and benefit from improved mixing and mass transfer [41]. In the synthesis of functionalized indolines, the reaction time was optimized by evaluating the effect of different sonication times on the conversion rate of the reaction. The study found that longer sonication times led to higher conversion rates, with a sonication time of 60 s providing the highest conversion rate of 98%wt [40].

The frequency and wattage of the ultrasonic system are important parameters that can affect the efficiency of ultrasonic-assisted reactions. The frequency of the ultrasound waves can affect the size of the cavitation bubbles, while the wattage determines the power of the ultrasonic system, which affects the intensity of the ultrasound waves. The frequency of the ultrasound waves is typically between 20 kHz and 100 kHz for chemical reactions [42]. At these frequencies, the cavitation bubbles generated by the ultrasound waves can reach high temperatures and pressure, leading to chemical reactions. However, the optimal frequency can vary depending on the specific chemical system being studied. For example, in the ultrasonic-assisted synthesis of functionalized indolines, the researchers optimized the frequency and wattage of the ultrasonic system to achieve the high conversion of the reactants [43]. The wattage of the ultrasonic system determines the power of the ultrasound waves, which affects the intensity of the cavitation bubbles generated. A higher wattage can lead to more intense cavitation, which can increase the rate of chemical reactions. However, an excessive wattage can also lead to overheating and the degradation of the reactants, reducing the yields of the desired products. Therefore, it is important to optimize the wattage for each specific chemical system to achieve the highest yield and selectivity [39].

The continuous ultrasound bath offers several advantages over conventional ultrasound baths and other pretreatment methods. By maintaining a constant flow of fresh solvent through the ultrasound bath, the continuous system prevents the buildup of contaminants and maintains the effectiveness of the ultrasonic cleaning or processing over a longer period of time [44]. This helps to improve the efficiency and consistency of ultrasound-based processes. Additionally, ultrasound pretreatment has been shown to increase the moisture diffusivity and decrease the drying time by 13–17% compared to untreated samples [45]. The continuous ultrasound bath can potentially provide more effective pretreatment, further enhancing the drying performance. Ultrasound-assisted alkaline pretreatment can also significantly improve the extraction of valuable chemicals from biomass, and the continuous system can optimize parameters like the solid/liquid ratio, ultrasound amplitude, and temperature to maximize yields [46].

However, the continuous ultrasound bath also faces potential limitations and challenges. To achieve the desired performance, the system requires the careful optimization of factors such as the solvent flow rate, ultrasound power, temperature, and pretreatment duration. Improper settings may lead to suboptimal results [47]. Ensuring uniform ultrasound exposure and solvent flows throughout a larger continuous system may present engineering challenges, and the proper design of the bath geometry and flow path is crucial for consistent pretreatment. Additionally, the continuous system must be compatible with the wide range of solvents used in various applications, and material selection and corrosion resistance are important considerations. While ultrasound pretreatment can reduce the overall drying time and energy use, the continuous system itself requires additional energy to pump the solvent and maintain the ultrasound field, and optimizing the energy efficiency is important for practical applications [48].

5. Biomass Specifications

Biomass valorization through ultrasound involves the use of ultrasonic technology to enhance the conversion of biomass into valuable products. Ultrasound can help with the extraction and hydrolysis of lignin, cellulose, and hemicellulose, which are the main components of biomass (Figure 4).

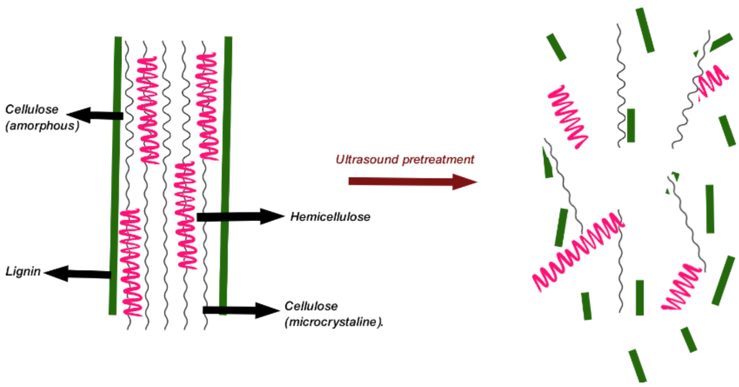


Figure 4. Mechanism of ultrasonic pretreatment.

Lignin is a complex aromatic polymer that is often considered a waste product in biomass processing. However, it has the potential to be valorized into high-value products such as phenolic monomers, which can be used in the production of bio-based chemicals and materials [43]. Ultrasound can help with the extraction of lignin by breaking down the complex structure of the biomass, making it easier to separate the lignin from the cellulose and hemicellulose [49]. Ultrasound can also help with the depolymerization of lignin, which is necessary to convert it into phenolic monomers. This process involves breaking down the large lignin molecules into smaller fragments, which can then be converted into phenolic monomers through further processing.

Cellulose and hemicellulose are carbohydrate polymers that can be converted into sugars through hydrolysis. Ultrasound can help with the hydrolysis of cellulose and hemicellulose by increasing the surface area of the biomass, which makes it easier for the enzymes to access the cellulose and hemicellulose [50]. Ultrasound can also help with the solubilization of the hemicellulose fraction as xylose, which can be further processed into bio-based chemicals and materials [50].

Ultrasound can also help with the hydrolysis of biomass by increasing the rate of the reaction and reducing the amount of energy required for the process. This is because ultrasound can create cavitation bubbles, which generate high temperatures and pressure when they collapse. These high temperatures and pressure can help to break down the complex structure of biomass, making it easier to extract the valuable components [51].

In addition to these benefits, ultrasound can also help to reduce the amount of energy required for biomass processing. This can reduce the amount of energy required for the extraction process, which can help to reduce the overall cost of biomass processing [51].

Furthermore, ultrasound technology can be utilized to assist in the production of bio-products from agricultural residues, offering an economically efficient and environmentally friendly waste management practice [52]. By utilizing ultrasonication techniques, researchers and industrial practitioners can explore new avenues for the conversion of agricultural residues into high-value compounds, contributing to the development of a sustainable bioeconomy [52]. Despite the challenges associated with scaling up ultrasound-assisted processes to an industrial level, the technology has demonstrated the potential to outperform conventional methods, offering a sustainable and efficient approach to biomass valorization.

The physicochemical characteristics of peapods, such as the density, lignin content, hemicellulose content, cellulose content, humidity, ash, fiber, and thickness, are crucial for the design of an ultrasound system for waste valorization (Table 3). These characteristics can significantly affect the efficiency of the ultrasound-assisted extraction of valuable components from peapods, such as protein, fiber, and bioactive compounds. For instance, the density of peapods can affect the penetration of ultrasonic waves, while the presence of lignin, hemicellulose, and cellulose can influence the extraction yield and the quality of the extracted components. The humidity and ash can impact the ultrasound system's performance by altering the acoustic properties of the medium. The fiber content and thickness of peapods can also affect the extraction efficiency and the energy requirements of the ultrasound system. Therefore, a thorough understanding of these physicochemical characteristics is essential when designing an ultrasound system that optimizes the extraction yield, preserves the quality of the extracted components, and ensures the sustainability of waste valorization processes.

Table 3. Physicochemical parameters of peapods.

Physicochemical Parameter	Result (%w)	Source
Bulk density (g/mL)	0.65 ± 0.01	[53]
Moisture	7.77	[54]
Volatile matter	74.18	
Ash	4.22	
Fixed carbon	13.0	
Cellulose	20.2	
Hemicellulose	17.4	
Lignin	5.0	
Electrical conductivity (µs/cm)	589 ± 0.10	[53]
pH	8.84 ± 0.08	[53]
Water-holding capacity (%)	200 ± 1.00	[53]

One of the key advantages of the ultrasonic pretreatment process is its ability to avoid the generation of inhibitory compounds, such as hydroxymethylfurfural (HMF), furfural, acetic acid, and formic acid [55]. These compounds can have a detrimental effect on subsequent processes, such as enzymatic hydrolysis and fermentation, by inhibiting the activity of enzymes and microorganisms [56]. The ultrasonic pretreatment process, with its unique mechanism of action, is able to break down the lignocellulosic biomass without producing these inhibitory compounds. This is a significant advantage, as it ensures that the downstream processes can proceed without the interference of these inhibitory substances, leading to improved overall efficiency and productivity.

In addition to the elimination of inhibitory compounds, the ultrasonic pretreatment process also enhances the accessibility and digestibility of the lignocellulosic biomass [57]. The high-frequency sound waves generated during the ultrasonic pretreatment disrupt the complex structure of the biomass, breaking down the lignin–hemicellulose–cellulose matrix and increasing the surface area available for enzymatic hydrolysis. This improved accessibility and digestibility of the biomass can lead to higher yields of fermentable sugars, which can then be utilized in various downstream processes, such as the production of biofuels, biochemicals, and other value-added products.

6. Mathematical Model

In ultrasound pretreatment, there is a cavitation effect produced by the rapidly vibrating transducer, causing waves to enter the liquid. Due to the change in pressure, cavitation bubbles are created, which contract and expand, generating a cycle dependent on the same change. To explain cavitation, the acoustic pressure is used, as in Equation (1) [58–60].

$$\nabla \times \left(\frac{1}{\rho_f}\nabla * p\right) - \frac{\omega^2}{\rho_f C^2}p = 0 \quad (1)$$

When a voltage is applied to the electrical part, it vibrates and causes a displacement vector in the solid interface, which is defined as in the following Equation (2). This domain is transferred to the liquid domain. The acoustic pressure can be calculated by solving the differential Equation (3) [58].

$$\begin{pmatrix} M_{uu} & 0 \\ 0 & 0 \end{pmatrix}\begin{Bmatrix} \ddot{u} \\ \ddot{V} \end{Bmatrix} + \begin{pmatrix} C_{uu} & 0 \\ 0 & -C_{vv} \end{pmatrix}\begin{Bmatrix} \dot{u} \\ \dot{V} \end{Bmatrix} + \begin{pmatrix} K_{uu} & K_{uv} \\ K_{uv} & -K_{vv} \end{pmatrix}\begin{Bmatrix} u \\ V \end{Bmatrix} = \begin{Bmatrix} F \\ Q \end{Bmatrix} \quad (2)$$

$$\left(-\omega^2[M_F] + j\omega[C_F] + [K_F]\right)\{p\}\Big) = \{f_F\} \quad (3)$$

Then, the acoustic waves move from the interface to the tank wall, and the area can be calculated with the following Equation (4) [58].

$$\left(-\omega^2\begin{pmatrix} M_s & 0 \\ \rho_f R^T & M_F \end{pmatrix} + j\omega\begin{pmatrix} C_2 & 0 \\ 0 & C_F \end{pmatrix} + \begin{pmatrix} K_s & -R \\ 0 & K_F \end{pmatrix}\right)\begin{Bmatrix} u \\ p \end{Bmatrix} = \begin{Bmatrix} f_s \\ f_F \end{Bmatrix}\ldots \quad (4)$$

A frequency signal is produced by the ultrasonic generator and is applied to the ultrasonic transducer; this frequency can be calculated with Equation (5) [61].

$$f_r = \frac{1}{2\pi\sqrt{L1bC1a}} \quad (5)$$

where f_r is the transducer frequency, $L1b$ is the impedance inductor, and $C1a$ is the total transducer capacitance.

Equation (6) shows the calculation of the ultrasonic power (P). The ultrasonic power gives the density of the acoustic power (W) with the total volume of extraction (L); the acoustic power is understood as the power supplied to the immersion fluid [62].

$$P = MC_p\frac{dT}{dt} \quad (6)$$

where M is the mass of the solvent (kg) and C_p is the heat capacity of the solvent (J/kg K).

The quantity of power for a unit of volume is defined similarly to the power density and is calculated with Equation (7) [63].

$$Pd = \frac{P}{V_L} \quad (7)$$

where V_L is the liquid volume. In addition, the wavelength (λ) for liquids, used to determine the optimal liquid height/volume conditions, is defined as in Equation (8), where c is the speed of sound in water and f is the applied frequency [63].

$$\lambda = \frac{c}{f} \tag{8}$$

Finally, it is important to quantify the cavitation yield (%) with the concentration of the product ($C_{product}$) and the ultrasound irradiation time (t) [63].

$$\% = \frac{C_{product} \cdot V_L}{t \cdot P} \tag{9}$$

Additionally, it is important to determine the specifications of the components. In this case, it is necessary to define the type of pump, the pipeline, and the valves for the continuous system. It is known that this pretreatment involves working with liquids—principally water or organic solvents. The characteristics of these liquids are similar; for this reason, the design is focused on water. Supported by the literature, the pump selected is centrifugal and we use ball valves [64–67].

7. Specifications and CAD Design

This work starts with a theoretical model and the experimental basis found in the literature. For each experimental process, it is necessary to define the products to be obtained and then select the frequency and power, which are parameters provided by the equipment. Then, the residence time is defined according to the selected lignocellulose biomass. The advantage of this system is that its process is continuous, which is why it allows the pumping of the product from the tank to the steel vessel and out of the vessel. This allows samples to be collected during the ultrasonic process.

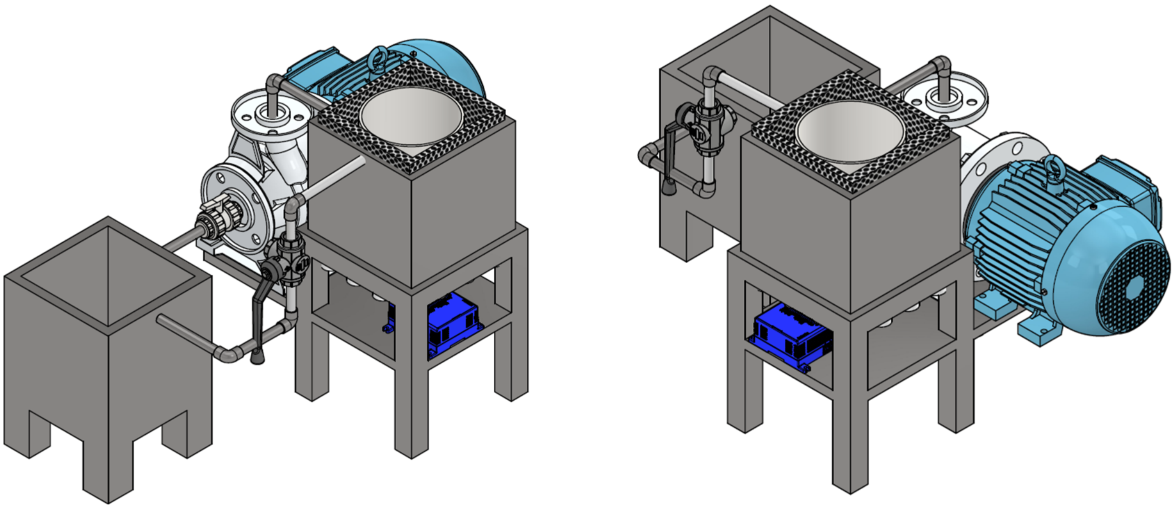
The equipment is designed in the Inventor program, version 2023. The design process starts with the tank volume to give the equipment a specific scale. The ultrasound generator and the frequency controller are selected from the EMERSON catalog. The catalog recommends the number of transducers for conversion, and this is the number used in the design. From this, we define the volume of the steel vessel and the pump that fulfils the necessary conditions to pump it. Finally, the selection of the pipe diameter and the corresponding valves for the process is performed. From the designed model, we proceed to the selection of the materials for the parts, where each one complies with the characteristics for the treatment of lignocellulose biomass and the temperature conditions for the process.

Applying the mathematical model and continuing with the process, the drawing is obtained, which is presented in Figure 5.

This continuous system is an ultrasonic bath adapted to a system of pumps with pipelines and valves, where it is possible to control the liquid flow and perform sampling during the process. The ultrasonic bath has a controller to define the frequency, and this system can operate in different conditions for ultrasound pretreatment. This equipment is designed with a capacity of 5 L; however, it is recommended to work with up to 75–80% of the total volume for optimal conditions and to prevent experimental accidents. It is important to consider that the total volume consists of a mixture of the biomass and liquid, and it can be changed according to the experimental test being performed. Additionally, it is important to highlight this equipment is designed with stainless steel variations of ANSI 304 and structural steel, which has more resistance. The characteristics are shown in Table 4.

According to the recommendations regarding the optimum capacity of the model, the experimental design has a capacity of 4 L, and, based on the power provided (260 W), we define the necessary reaction time.

Below, in Figure 6, we present the parts and their names. Meanwhile, in Figure 7, some dimensions are shown.



(**a**) (**b**)

Figure 5. Computer-aided design of continuous ultrasound treatment. (**a**) Right-side view of continuous ultrasound device and (**b**) left-side view of continuous ultrasound device.

Table 4. Characteristics of continuous ultrasound device.

Characteristic	Value
Volume of steel glass (L)	5
Frequency (kHz)	40, 80, 120
Nominal power (W)	260
Transductor	16
Pump	VOGT N610

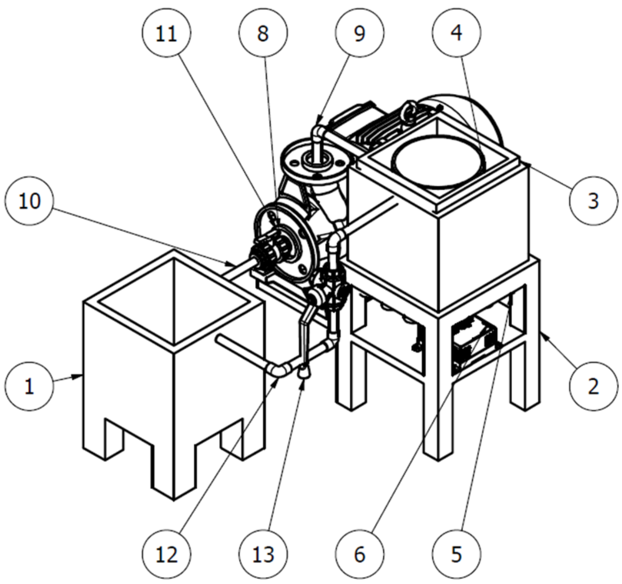


Figure 6. Parts of continuous ultrasound device. 1. Inlet/outlet tank. 2. Rigid structure. 3. Mesh. 4. Steel glass. 5. Transductors. 6. Controller. 7. Ultrasonic generator. 8. Pump. 9. Inlet pipeline. 10. Inlet pipeline to pump. 11. Ball valve. 12. Outlet pipeline. 13. Three-line ball valve.

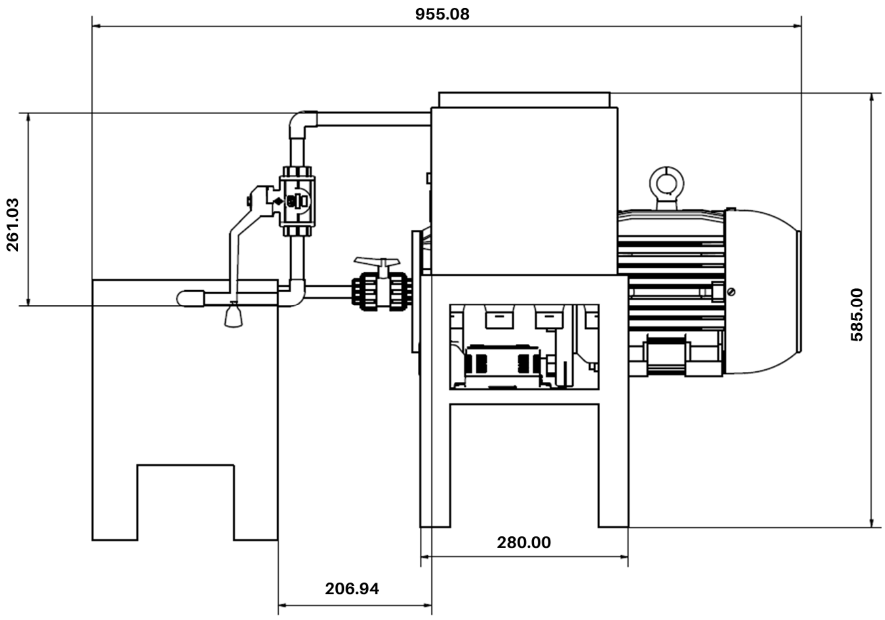
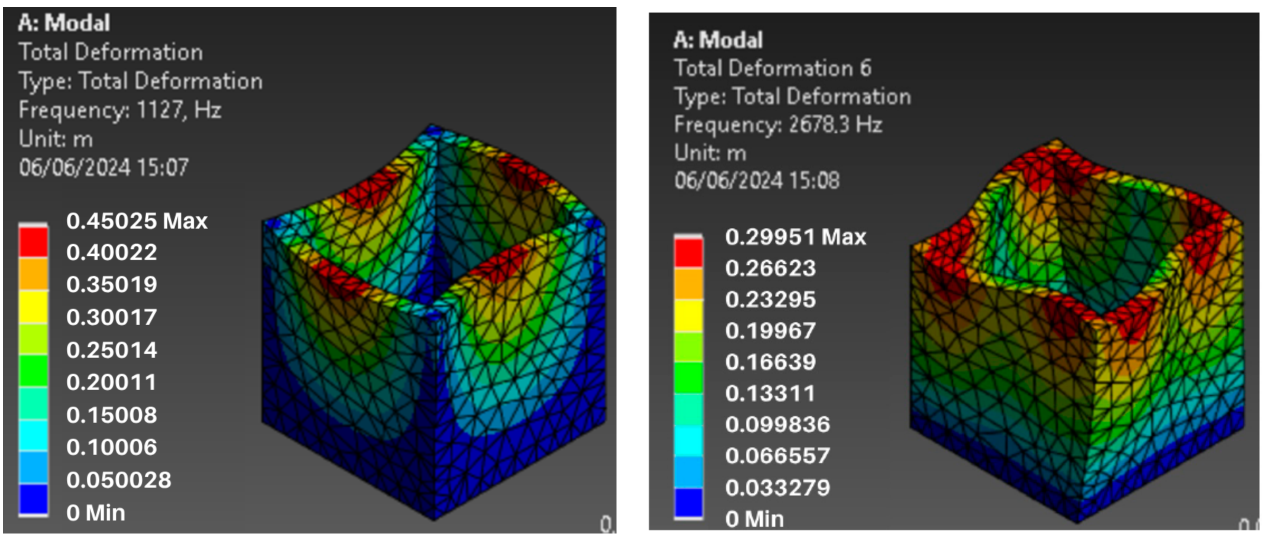


Figure 7. Dimensions of continuous ultrasound device. These dimensions are in millimeters.

8. Finite Element Analysis

In this section, a modal analysis is performed to determine the frequency behavior of the parts with respect to the applied loads. The most important parts for ultrasonic pretreatment are the tank and rigid structure, because these are the critical parts for the operation of the equipment when the generator is started and vibration occurs. Using the ANSYS program, the tank was meshed for analysis, and fixed support was defined at the bottom of the tank. This process was simulated in different modes, where the deformation of the tank at the different frequencies supported by the part was evidenced. Likewise, it was evidenced that the largest deformations occurred in the central parts and the corners of the upper part. Figure 8 shows the modal analysis, where a deformation sequence is displayed at a minimum frequency of 1127 Hz with 0.45025 m of deformation up to 2678.3 Hz with 0.29951 m of deformation.



(**a**) (**b**)

Figure 8. Modal analysis for tank. (**a**) Deformation for the low frequency. (**b**) Deformation for the high frequency.

To solve the harmonic response of this part of the design, in addition to the fixed support, a weight force that the tank could withstand according to its volume was established. This was followed by a harmonic response (Figure 9), showing the total deformation of the tank, where the maximum deformation occurred in the upper center with a value of 2.05×10^{-10} m. The frequency response graph is shown in Figure 10.

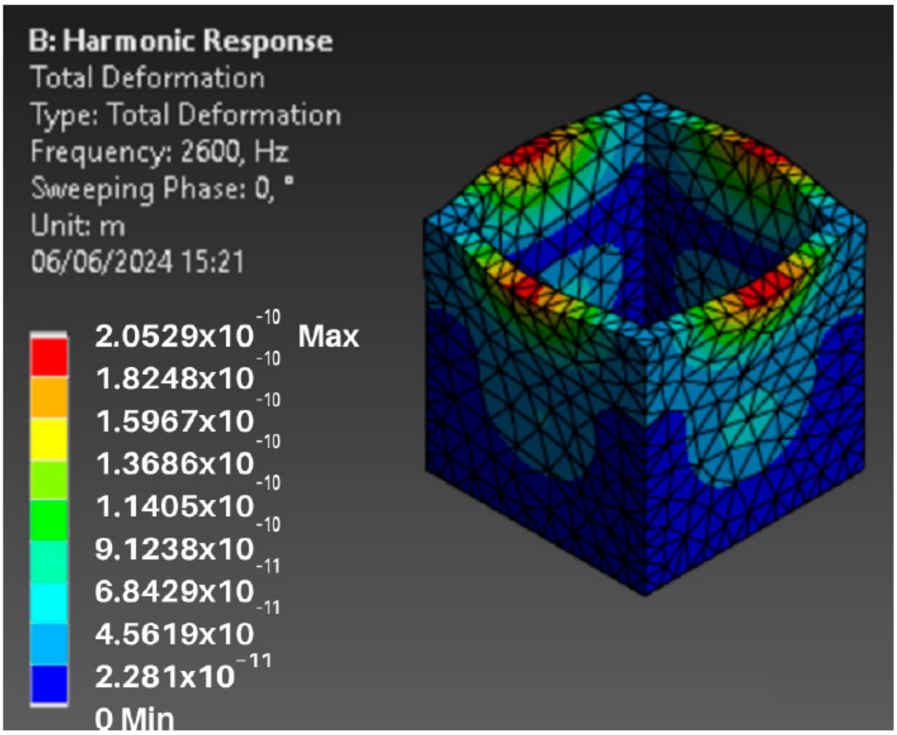


Figure 9. Total deformation of the tank for the higher frequency.

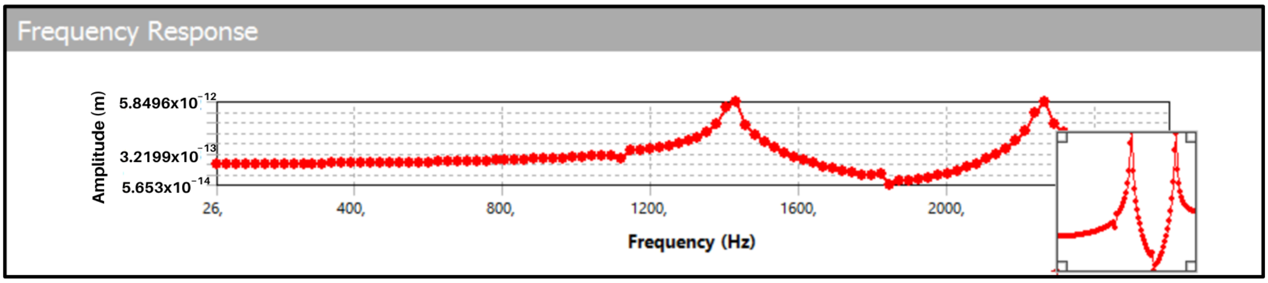


Figure 10. Analysis of the frequency response.

This analysis is beneficial because it simulates the scenario to which the structure will be exposed and it is possible to conclude that the equipment can meet the frequency range that was established.

9. Conclusions

The application of ultrasonic pretreatment is a critical step in improving the efficiency of processes involving the conversion of biomass to liquid by cavitating the passage of ultrasonic waves through the medium. According to the literature, the use of this pretreatment technique can greatly increase the overall bioconversion efficiency of lignocellulosic biomass into biofuels and biochemicals. Ultrasonic pretreatment increases the specific surface area and decreases the degree of polymerization by dismantling the structural barriers within the biomass, which in turn allows the compounds in the liquid to react chemically. Their further utilization will depend on the optimization of parameters such as the frequency, power, and type.

A device for the continuous ultrasound process that operates with lignocellulosic biomass is proposed. This is an innovative device for the industry and can be evaluated with different manufacturing materials to increase its efficiency and useful life. The continuous system can obtain better and/or different results and consequently reduce the time consumed in the process.

Finally, we present a unit with a capacity of 5 L and power variations of 40, 80, and 120 kHz, operating at a power level of 260 W. Additionally, it has a piping system and valves that operate in favor of the continuity of the process and addresses the lack of access to the product. Finally, it has a rigid structure that supports its components, as well as the pump and the vibration that it produces.

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